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TSUNAMI FORECASTING

By

Doak C. Cox

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Contents

Introduction

Tsunamis are trains of long waves in the ocean, having periods from several minutes to about an hour, impulsively generated as by faulting of the ocean floor or by submarine landsliding (Cox, 1963a). Storm surges, which are long waves generated by atmospheric disturbances, and tsunamis are commonly know as tidal waves, although they resemble the true tides only in manifesting, sometimes and at some places, gentle rises and falls of water level. Because tsunamis are usually associated with earthquakes, they have also been called seismic sea waves.

Although in mid-ocean the height of tsunami waves is small, in shallow water the wave height increases greatly, and the waves may be very destructive where they run up on shore. The tsunami generated off the coast of Chile at the time of the great earthquake of 22 May 1960 rose on the Chile shores to heights of as much as 60 feet, killing about 1000 people and causing many millions of dollars of damage to ships, docks, and buildings (Saint-Amand, 1961; Sievers and others, 1963). This same tsunami, sweeping across the Pacific, rose to more than 30 feet above sea level at Hilo in the Hawaiian Islands, killing 60 people there, and causing $27 million of damage (Eaton, Richter, and Ault, 1961). Still farther away, it swept the shores of northern Honshu Island, Japan, to heights of as much as 15 feet, killing 229 people, and causing more millions of dollars of damage (Takahasi, 1963). Obviously, warnings of the generation and approach of a tsunami save lives, and protective structures reduce risk to persons and property.

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Origin, General Characteristics, and Behavior of Tsunamis

Tsunamis originate most commonly in the seismically active belt surrounding the Pacific Ocean. Iida (in preparation) has found records of more than 350 tsunamis in the Pacific, of which about 120 were generated near Japan, about 50 off the shores of South America, about 50 in seas of the East Indies, and about 30 off the shores of the Kuril Islands, Kamchatka, and the Aleutian Islands. Other Pacific generating areas have been in the vicinities of New Zealand, Tonga, Samoa, Fiji, the Solomon Islands, New Guinea, the Philippines, North America, the Hawaiian Islands, the Marshall Islands, and the Mariana Islands.

Tsunamis have also been frequently generated in the Mediterranean Sea, especially in the vicinity of the Greek Islands but also near the coasts of Turkey, Israel, Southern Italy, France, and Spain. Tsunamis rarely occur in the Atlantic, except in the vicinity of the Caribbean Islands, although they have also been generated on the Grand Banks, off Portugal, and near the Azores. A few tsunamis are known to have been generated in the Indian Ocean.

TABLE 1. AREAS OF ORIGIN, MAXIMUM RUNUP HEIGHTS, AND EFFECTS OF THE MOST SIGNIFICANT TSUNAMIS OF THE LAST CENTURY

DATE	SOURCE	MAXIMUM RUNUP HEIGHT	EFFECTS
1867 Nov. 18	Caribbean	60 ft. at Guadeloupe	Widespread damage throughout Caribbean
1868 Apr. 2	Hawaii Island	60 ft. on southeast coast of Hawaii Island	81 deaths; 2 villages swept away
1868 Aug. 13	Arica, Peru	70 ft. at Concepcion	24 ft. drawdown at Iquique; extensive damage in Hawaii
1871 Mar. 2	Tagulandang I., Dutch East Indies	84 ft. at town of Buhias	600 ft. inundation; much damage
1877 May 9	Chile	75 ft. at Arica	Widespread damage; 5 deaths; 37 houses destroyed in Hilo, Hawaii
1878 Jan. 10	New Hebrides	40 ft. at Tanna Island	
1883 Aug. 26	Sunda Strait	135 ft. at Mera, Java	Resulted from explosion of Krakatoa volcano; subsequent waves generated atmospheric pressure disturbances observed world wide
1896 June 15	Sanriku Coast, Japan	100 ft. at Kamaishi	27,122 deaths; 10,617 houses swept away
1899 Sept. 10	Yakutat Bay, Alaska	30 ft. in bay only	No wave at sea
1908 Dec. 21	Messina Strait, Italy	39 ft.	
1909 July 30	Mexico	30 ft. at Acapulco	

TABLE 1. (Continued)

DATE	SOURCE	MAXIMUM RUNUP HEIGHT	EFFECTS
1917 May 1	Kermadec Islands	40 ft. at Samoa	Wave recorded on west coast of U.S.
1918 Aug. 15	Mindanao, Philippine Islands	24 ft. at Mindanao	100 deaths
1918 Sept. 7	Kuril Islands	40 ft. at Nemuro, Japan	24 deaths; 10 ft. Hawaii and San Francisco
1918 Oct. 11	Northwest coast, Puerto Rico	18 ft. at Point Jiguero	328 ft. inundation at Aguadilla, causing 30 deaths
1922 Nov. 11	Coquimbo, Chile	30 ft. at Chanaral	$1\frac{1}{2}$ miles inundation at Coquimbo; 1,000 deaths; many homes destroyed
1923 Feb. 3	East coast of Kamchatka	26 ft. in Kolygir Bay	26 ft. along southern coast of Kamchatka; 20 ft. in Hawaii; 6 deaths at Hilo, Hawaii
1923 April 13	Gulf of Kamchatka	65 ft. in gulf	18 deaths; many canneries and buildings destroyed
1923 Sept. 1	Kwanto, Japan	35 ft. in Sagami Bay	868 houses swept away
1925 Nov, 16	Mexico	35 ft. at Zihautcanejos (west end of state of Guerrero)	
1933 Mar. 2	Sanriku coast, Japan	96 ft. in Ryori Bay	2,986 deaths; 4,086 houses swept away
1944 Dec. 7	Tonankai, Japan	33 ft. in Owase	998 deaths; 3,059 houses swept away
1946 Apr. 1	Aleutian Islands	20 ft. in Hawaii	68 deaths, 250 buildings destroyed, $27 million damage in Hilo; Hawaii death total 159

TABLE 1. (Continued)

DATE	SOURCE	MAXIMUM RUNUP HEIGHT	EFFECTS
1946 Dec. 20	Nankaido, Japan	22 ft. on Kii Peninsula	1,500 deaths; 2000 houses swept away
1952 Nov. 4	Kamchatka	65 ft. along east coast of northern Kuril Islands	12 ft. at Talcahuano, Chile; $285,000 damage in Hawaii
1956 July 9	Grecian Archipelago	100 ft. at Amorgos I.	
1957 Mar. 9	Aleutian Islands	52 ft. Kauai I., Hawaii	$3,000,000 damage in Hawaii
1958 July 10	Lituya Bay, Alaska	1740 ft. in Lituya Bay	Resulted from rockslide triggered by earthquake; effects negligible outside bay
1960 May 22	Chile	35 ft. at Hilo, Hawaii	61 deaths, 537 buildings destroyed, $22 million damage in Hilo; 33 ft. at Valdivia, Chile
1964 Mar. 28	Kodiak - Prince William Sound, Alaska	60 ft. on Kodiak Island	Damage severe and widespread along coastline; at least 100 deaths; severe damage at Seward, Valdez, Whittier, and Kodiak

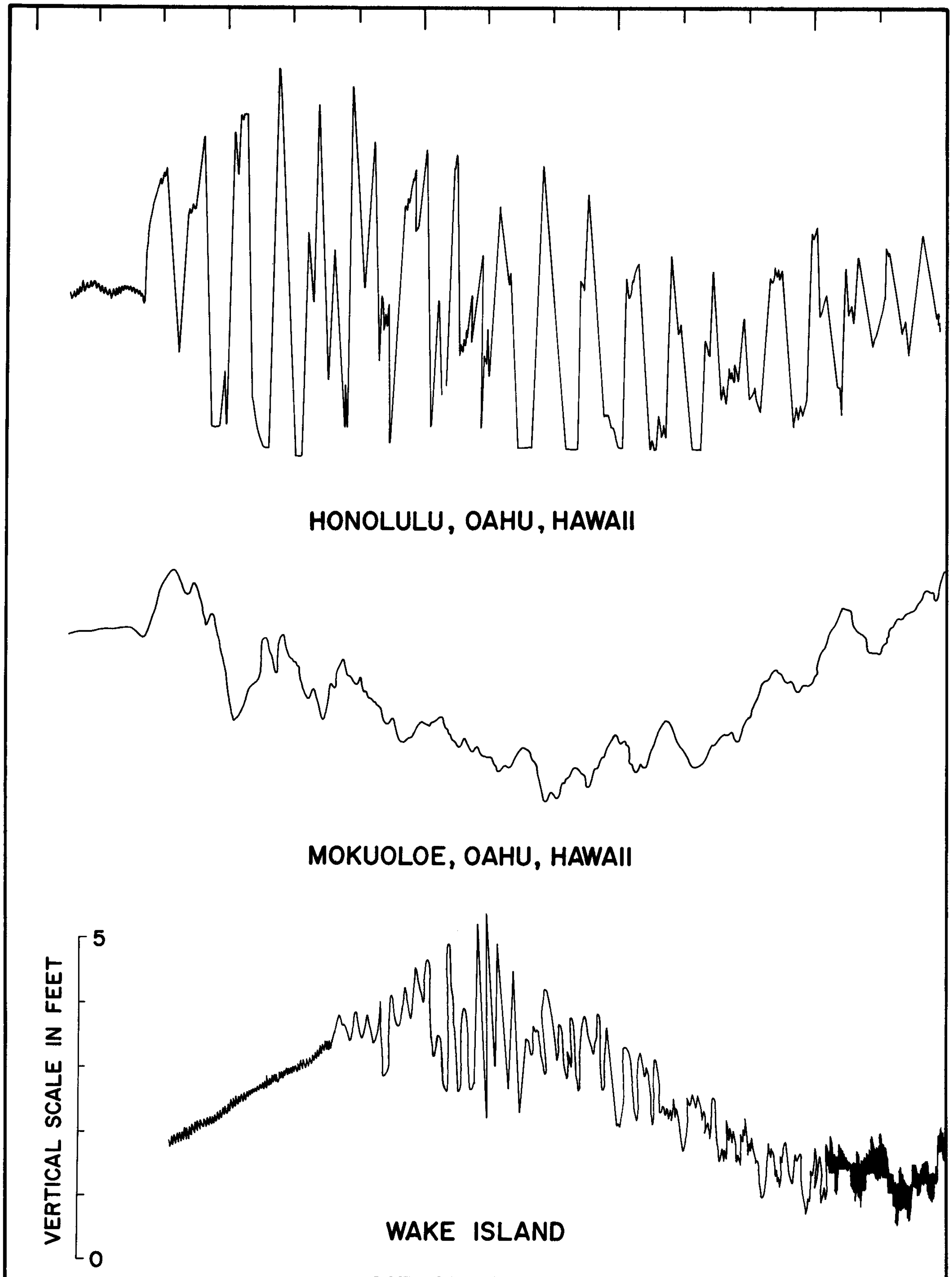

Fig. 1. The 1960 tsunami as recorded by a few tide gages.

Table 1 shows the areas of origin, the maximum runup heights, and the effects of the most significant tsunamis of the last century.

The association of tsunamis with earthquakes suggests that they are generated by the sudden fault displacements of the ocean floor that cause the earthquakes. Tsunamis may also be generated, however, by submarine landslides that may be triggered by the earthquakes, by subaerial landslides slipping into the water, or by volcanic explosions or collapses. Essentially the same kind of wave trains may be generated by sufficiently large artificial submarine or surface explosions, such as nuclear explosions. All of these modes of generation are sudden, or impulsive, as contrasted with the continuing atmospheric pressure disturbances that generate storm surges.

It is important to recognize that tsunamis are not single waves but trains of successive waves. The largest wave is frequently not the first but, commonly, the third or some later wave in the train, as shown in Figure 1. The term "long waves," as used in the definition of tsunamis, indicates that the wave lengths, that is the distances between successive waves in the train, are much greater than the depths of the ocean, even at its greatest depth. The waves in the important front sections of tsunami wave trains have wave lengths of at least 30 or 40 miles and sometimes, perhaps, of 300 or 400 miles. In contrast, the ocean is in general only about 3 miles deep, and in its deepest trenches, only about 7 miles deep.

Because their wave lengths are so great in comparison with the ocean depth, tsunami waves behave as "shallow-water" waves whose velocity is proportional to the square root of the depth. In mid-ocean (2400 to 3000 fathoms depth) a tsunami travels with a velocity of about 400 to 450 knots. However as the water shoals near land, the tsunami velocity decreases, so that in water of 150 fathoms depth it is traveling at only about 100 knots, and in water of 10 fathoms, about 25 knots. Along with the decrease in velocity, and concurrent decrease in wave length, there is an increase in height. The waves of even a large tsunami may be only about a foot high in mid-ocean. In water of 150-fathom depth, however, the height would approsimately double, and it would double again where the water depth decreases to 10 fathoms.

As the waves of a tsunami spread out from the point of origin, they do not remain regular, but develop salients and re-entrants where they have moved, respectively, over deeper and shallower water. Concomitantly, the energy in the waves diverges and converges in a complicated way leading to variations in wave heights along the same wave. As the waves move near shore this behavior becomes increasingly complex and other processes induce differences in energy and height from place to place. Large abrupt discontinuities in depth, for example, lead to partial reflection of energy back to sea. The waves may set into oscillation the water of harbors and bays whose natural periods match those of the tsunami. The sides of bays may guide the waves in such a way as to cause increases in height. The waves may increase so greatly in height and steepness that they break and form bores similar to those caused by extreme tides. The resonant and other nearshore modifications are so effective that the same tsunami generally manifests itself in quite different characters on different shorelines, as indicated in Figure 1.

The width to which the waves finally inundate a coastline and the runup heights to which they finally attain are controlled complexly by their heights and velocities as they cross the shoreline, and by the steepness and roughness of the coast. The runup heights attained in a single tsunami, one which may have been only about a foot high in mid-ocean, may range from only a foot or two along one part of a shoreline to 20 or 30 feet at others. At some places the water may rise and fall gently with the arrival of successive crests and troughs of a tsunami, while at other places the same waves may rush on shore with great violence. Where the rise and fall are gentle, even when the waves are high, the damage may be limited to remarkably gentle floating of frame buildings off their foundations plus the effects of wetting. Where the onshore velocity is high, buildings may be smashed, huge rocks rolled around, and so forth.

Tsunami Warning Systems

Warnings of the approach of high tsunami waves may be based on seismic observations or on observations of the early, frequently small, waves of a tsunami. In Japan, where the frequency of tsunamis is great, local informal warning systems have operated sporadically for centuries, based on remembered or traditional experience. Formalization of the warnings was recommended early (Wakayama, 1896), and the requisite public education has been repeatedly re-emphsized (Imamura, 1935; Takahasi, 1935; Wadati, 1948). The present Japanese system, which was organized in 1941 by the Japan Meteorological Agency, may be thought of as an outgrowth, formalization, and integration of these local warning systems (Inoue, 1951; Wadati and others, 1963).

Warnings of tsunamis generated off the coasts of Japan are based on seismic information provided by 26 well-distributed, continously-manned, seismograph stations reporting to 5 regional centers. Within 10 minutes of the occurrence of an earthquake of specified minimum intensity the seismographic stations report to appropriate centers the time of arrival of the P (primary or compressional) seismic waves, the interval between P and S (secondary or shear) waves, the maximum seismic amplitude, and the direction of initial motion. Within 20 minutes the centers determine the location of the epicenter (point on the surface over the focal point or point of initial disturbance), the focal depth, and the magnitude of the earthquake. For a quake whose epicenter is on the shore or at sea, the tsunami risk is determined from a chart such as shown in Figure 2.

In such a diagram the maximum double amplitude of ground motion at various seismograph stations may be expected to plot, in relation to the S-P arrival time difference (or epicentral distance), roughly along a curve of earthquake magnitude such as the light curves indicated for magnitudes of 7.0, 8.0, and 8.5. Depending on whether most of the points plot below the heavy curve labeled minor tsunami earthquake, between the two heavy curves, or above the heavy curve labeled major tsunami earthquake, it is assumed, respectively, that no tsunami has been generated, a minor tsunami has been generated, or a major tsunami has been generated. The size of the tsunami on a given coast is estimated from the domain bounded by dashed lines within which falls the intersection of the magnitude line for the given earthquake and the epicentral distance line corresponding to the distance of the coast in question.

It should be noted that the relationships between tsunami magnitude and earthquake magnitude (see Iida, 1963), and between tsunami severity and the distance from the epicenter to the portion of the coast being warned, were developed empirically for the Japanese environment and should not be assumed to be valid elsewhere.

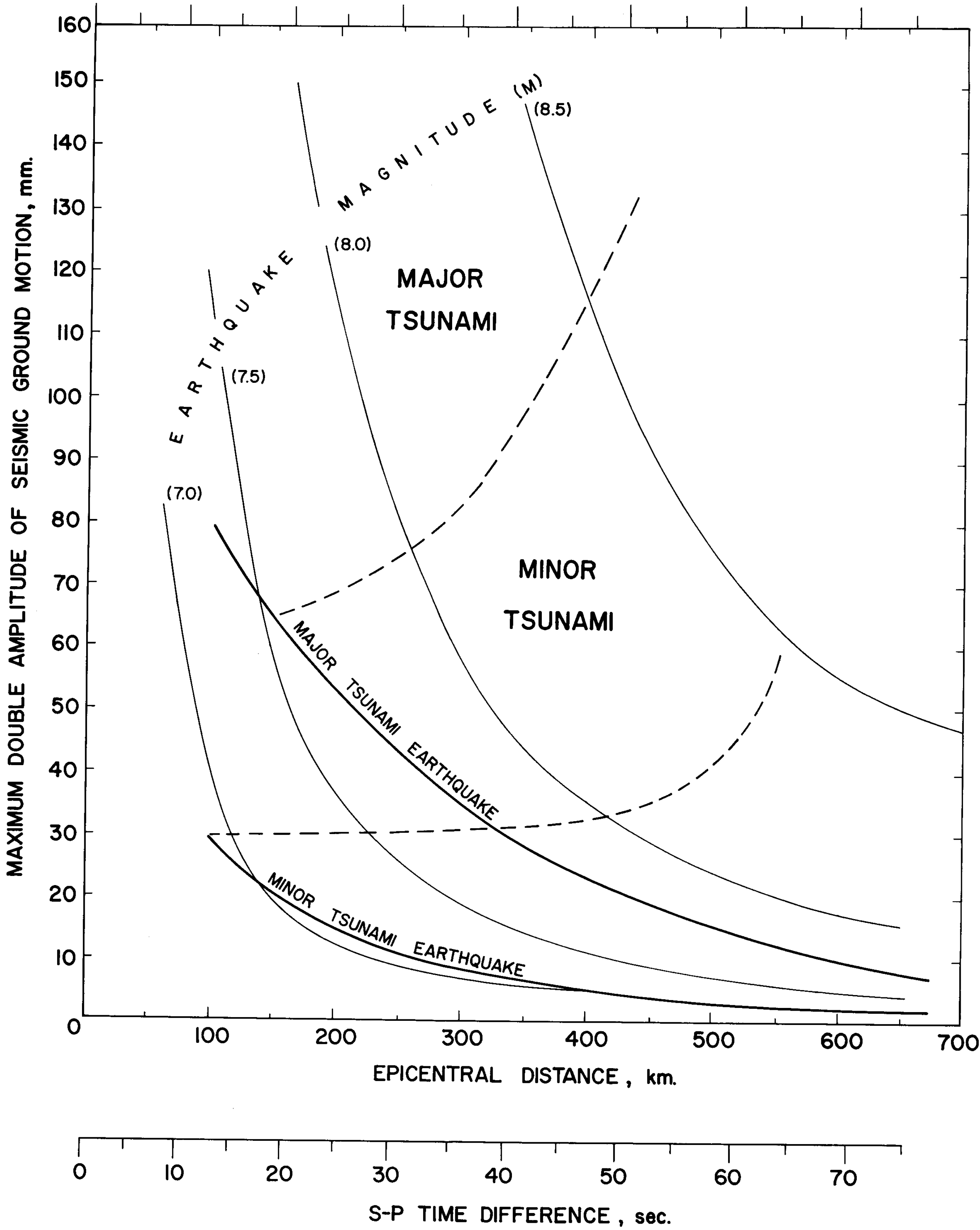

Fig. 2. Japan Meteorological Agency tsunami warning diagram.

A warning system similar to the Japanese system was established by the USSR in 1956, using seismograph stations at Petropavlovsk, Kamchatka; Kurilsk, on Iturup Island; and Yuzhno-Sakhalinsk, Sakhalin (Lavrentyev and Savarensky, 1963). Special attention has been given to the development of instruments for quick determination of distance and direction, and magnitude of strong earthquakes, using the data of one station.

Although tsunamis have been generated close to the coasts of Alaska, California, and Hawaii, tsunamis of distant origin are the major threat to U. S. coastlines. A tsunami warning system, with transoceanic capabilities, first suggested by Milne (1880), was realized in the early 1920's when the Hawaiian Volcano Observatory began issuing warnings in Hawaii based on seismographic information recorded at the observatory at Kilauea volcano (Finch, 1924). Confidence in the system was never high. The frequency of significant tsunamis was too low to promote the public tolerance of the false alarms that were inevitable considering the lack of confirmatory wave information, and the Observatory ceased to issue warnings in the 1940's.

The present U. S. tsunami warning system (Roberts, 1950; Zerbe, 1953; Cox (chrmn.), 1960; Spaeth, 1962) centered at the Honolulu Observatory of the Coast and Geodetic Survey was established following the Aleutian tsunami of 1946, which had disastrous effects in Hawaii. As in other systems the initial information is seismographic, but there is an essential difference from other systems in the use of marigraphic information for confirmation of the generation of a tsunami. One of the seismographs at the Honolulu Observatory is equipped with an alarm which sounds when the amplitude of seismic motion exceeds a certain value. The alerted Observatory personnel inspect the seismographic record, determine epicentral distance, and estimate direction and magnitude. If the source location and magnitude are such that a tsunami might be associated with the quake, telegraphic requests for additional information are sent to several or all of the 14 other seismograph stations involved in the system (Fig. 3). These stations may also initiate alerting procedures. With the information from the other stations, the earthquake epicenter is located and the magnitude confirmed. If the epicenter is within or on the border of the ocean, and the magnitude approaches or exceeds 7 on the Richter scale, tide-gage stations in the warning system nearest the epicenter and between the epicenter and coastlines to be warned are informed of the estimated time of arrival of the tsunami, which it is assumed might have been generated, and are requested to report any abnormal sea-level behavior that is experienced.

Thirty tide-gage stations are involved in the warning system. For each station a travel-time chart similar to that in Figure 3 has been prepared by the use of the long-wave velocity formula $C = \sqrt{gh}$, where C = velocity, g = acceleration of gravity, and h = depth. The chart in Figure 3 appears to show the successive positions of a long wave spreading out from Honolulu at half-hour intervals. Since the travel times are equal in reversed directions over the same path, however, the chart is intended to indicate the travel time of a long wave from any point in the ocean to Honolulu, and this chart, as those for other stations, is used for the prediction of arrival time of a tsunami or possible tsunami generated in association with a particular earthquake.

Advisory bulletins are released by the Observatory to appropriate military and civilian agencies in Hawaii, other Pacific islands, and the Pacific Coast states, whenever the risk of a tsunami appears sufficiently

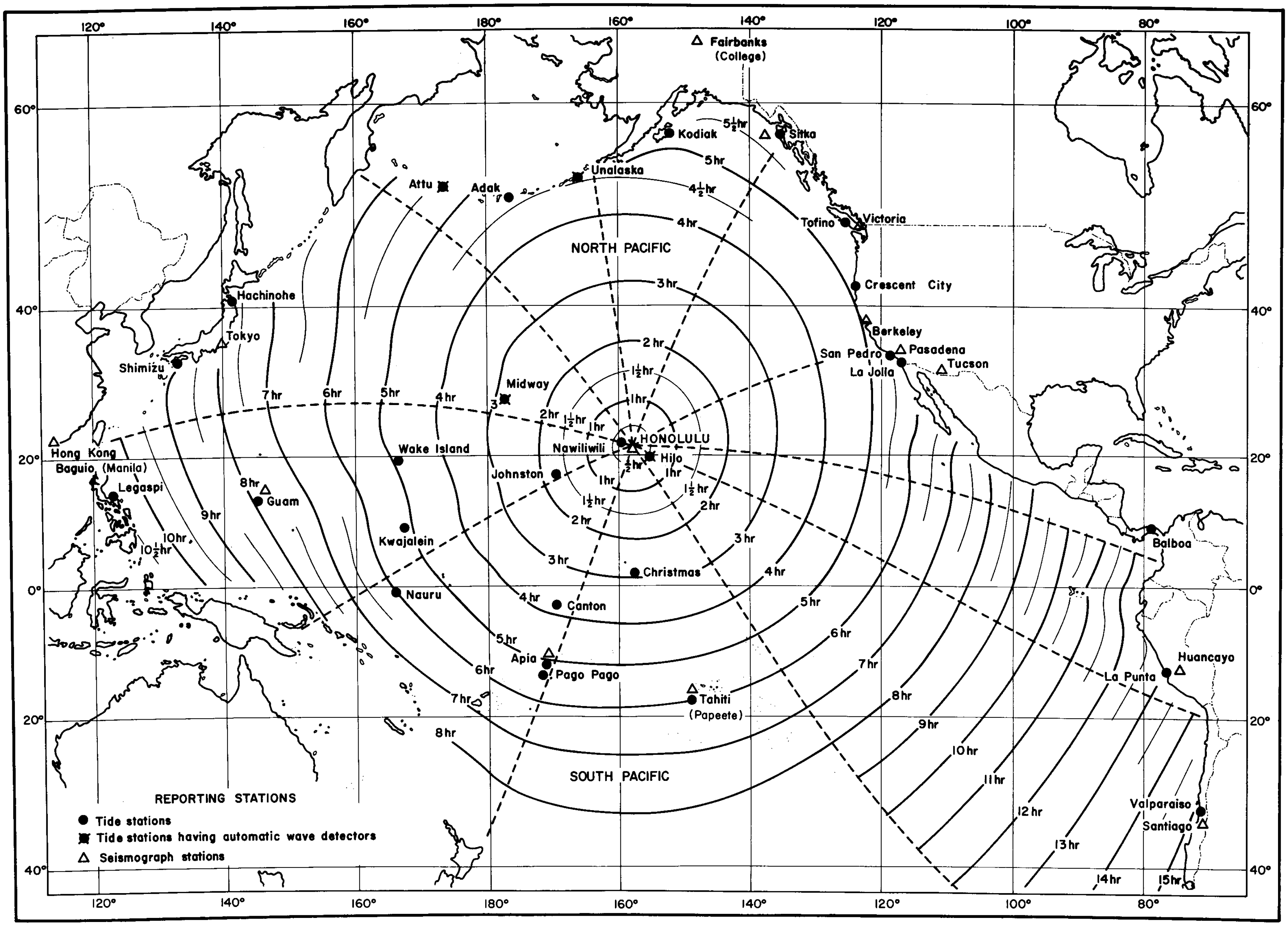

Fig. 3. U. S. Coast and Geodetic Survey tsunami travel-time chart, showing tsunami warning system stations.

great, generally in the case of an earthquake of magnitude 7 or larger in the Aleutian area, or $7\frac{1}{2}$ or larger elsewhere in the Pacific Ocean. Such bulletins include the estimated arrival time of the tsunami at the place to which the bulletin is sent. Warnings, as distinct from the advisory bulletins, are issued only under the following circumstances:

(1) Unusual sea-level disturbances having tsunami characteristics are recorded at one or more of the warning system tide stations scattered about the Pacific.

(2) No reply is received from a tide station in a critical recording position in response to a query from the Honolulu Observatory after the occurrence of an earthquake large enough to trigger the seismograph alarm.

(3) An earthquake occurs whose epicenter is in or on the borders of the Pacific Ocean in such a location that a tsunami generated there would not arrive at any tide stations sufficiently in advance of its arrival at a particular shoreline to allow warning that shoreline.

The handling of advisory bulletins and warnings varies somewhat between civilian and military agencies and from state to state. In Hawaii the civilian responsibility for propagating the warning lies with the Civil Defense Division of the State. Release of even the initial advisory bulletins through normal news media has been recommended (Cox, 1963b) to counteract the effects of unofficial and generally unreliable information. The warnings are transmitted by ordinary radio stations, with which the Civil Defense Division has direct contact, by signals sounded on coastal sirens, and by police and civil defense wardens. It is expected that a warning will be issued between one and two hours in advance of the arrival of the tsunami. No forecast of the height of the waves is possible because of the greatly differing effects of local topography, and the inhabitants of coastal areas are expected to evacuate to high ground whenever a warning is issued. Ships and small boats generally put to sea, and some mobile equipment on land is moved inland.

It should be remembered that the first wave of a tsunami, particularly of a large tsunami from a distant source, will in general not be the largest wave, and that the highest levels reached by the waves may come some hours after the estimated time of arrival of the tsunami. The determination of the appropriate time for reoccupancy of evacuated areas on a particular coast depends on the waves actually experienced at the coast in question, and the sequence of wave heights at points closer to the source. The Coast and Geodetic Survey has recommended that the warning period extend to not less than 2 hours after the estimated time of arrival of the waves.

Many cooperating stations in the Coast and Geodetic Survey's system, both seismographic and marigraphic, are in foreign countries and, through bilateral agreements, the Honolulu Observatory provides its warnings to Chile, New Zealand, Tahiti, Samoa, Fiji, Hongkong, the Philippines, and Taiwan, as well as to American states and territories. Information from Japan and warnings to Japan are handled through the Japan Meteorological Agency, which also provides, through the Khakarovsk weather broadcast station in Siberia, a link with the USSR system serving Kamchatka and the Kuril Islands. Strengthening of the international ties is to be encouraged.

Prediction of Tsunami Inundation and Effects

A warning system is of little value unless there are some definitions of the area being warned and the safe areas to which people may evacuate. As yet only rather generalized definitions can be given.

For a tsunami that is generated on the shelf or slope immediately off the Japanese shore the length of coastline that requires warning is defined by the Japanese warning diagram (Fig. 2). According to the experience used in the development of the diagram, the tsunami wave effects will be negligible along portions of the coastline that are more than 500 km from an earthquake epicenter, except in the case of an earthquake of extraordinary magnitude, and hence the more distant portions do not require warning. However, this limitation should not be assumed valid for other coasts where the relationship between tsunami magnitude and earthquake magnitude may be different and where different coastal and shelf configurations may be involved. Further, the limitation is completely invalid for tsunamis moving across the ocean, such as the tsunami generated off Chile in May 1960 which had disastrous effects in Japan, or such as all but one of the tsunamis that have caused damage in Hawaii.

In Hawaii the only differentiation that has yet been found to be generally practicable has been between certain coasts facing southwest, a direction from which no tsunamis have come during recorded history, and all other coasts (Cox, 1961). These southwest-facing coasts must still be evacuated during a tsunami warning, but not to as high an elevation nor as far inland. In general, the Hawaiian coastal zone, in which there seems from the historical record to be significant risk of inundation from tsunamis, is defined as that below a potential runup level $R = R_0 - .01D$, where R_o is a reference height above mean sea level, defined as 30 feet on the protected southwest coasts and as 50 feet elsewhere, and D is the distance inland from the minus 10-foot contour. Special provisions are made for the effects of narrow entrances to bays and lagoons and those of great widths of reef at depths greater than 10 feet below sea level. In a very few areas, for example at Hilo, the historical record indicates that the potential inundation zone is larger than that defined above, and its limits have been determined from the local historical inundation limits with a safety margin.

Protective Measures

It is, of course, physically possible to reduce the risk of inundation and damage by tsunamis at a particular place by artificial means, and in Japan certain kinds of protection have been provided for many years. The oldest protective measures were groves of trees planted along the shoreline to reduce the extent of inundation and the violence of attack by tsunami waves. Seawalls have also been constructed along the shore at many seaport towns, especially on the northeast coast of Honshu Island, which is particularly subject to attack by tsunamis. Even some flat, valley-bottom agricultural areas have been so protected.

Even where the runup is essentially two-dimensional, the effects of such seawalls is still somewhat uncertain; and the effects of breakwaters, generally involving three-dimensional effects, is still very uncertain indeed. The possibility of protection of the city of Hilo, Hawaii, by some combination of breakwaters and seawalls is under intensive study, including large-scale model experimentation (Corps of Engineers, 1960, 1962;

Hilo Tech. Tsunami Advisory Council, 1962). In the meantime, very positive protection has been provided by relocating the part of the city that was most subject to damage.

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